Conference discussion of the nuclear few-body problem: questions and issues

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During the final session of the conference participants discussed important questions and issues from the current study of the nuclear few body problem. The discussion was preceded by five very short “mini-summaries” (limited to about 5 minutes each) presented by each member of the panel. These “mini-summaries” are presented in Sec. 1 below, and the questions and discussion is summarized in Sec. 2. The “mini-summaries” are presented in Sec. 1 in the order they were given to the conference.

1. FIVE EASY PIECES: CONFERENCE MINI-SUMMARIES

1.1. Remarks by D. Drechsel

In the following I shall report on recent developments concerning the structure of the nucleon, its size, polarizability, deformation and spin structure. Due to the dimensions involved, these properties are usually quite relevant for our understanding of nuclear structure, and on the other hand most investigations of the neutron require a precise knowledge of the nucleus that serves as a “neutron target”.

The charge distribution of the neutron has now been studied by double polarization experiments in quasifree kinematics using electron scattering on ^{2}H or ^{3}He targets (see contribution of J. Jourdan). It had been pointed out some time ago that nuclear structure effects would be considerably reduced in such kinematics, but to the surprise of everybody

*The five mini-summaries in Sec. 1 were independently prepared by each panel member. The discussion in Sec. 2 was written by the panel chair using a tape recording of the discussion. Whenever possible, the name of the speaker is given, but in some cases the names could not be determined. All errors in the transcription of this discussion are the sole responsibility of the chair, and he apologizes for these in advance.

it still required a careful analysis of binding effects to determine the form factor at small Q^2, the square of four-momentum transferred by the virtual photon. As a result the electric form factor of the neutron, $G_E^n(Q^2)$, was found to be considerably larger than previously assumed. The electric charge distribution, obtained by a Fourier transform in the Breit frame, shows a positive peak at small distance r, a cross-over to negative values at $r \approx 0.7$ fm with a long tail extending to $r > 2$ fm. The positive core can be visualized as a "bare" nucleon or a three-quark bag with a proton configuration (uud), which is surrounded by a cloud of negatively charged pions (quark-antiquark fluctuations with the quantum numbers of the π^-).

Compared to an rms radius of a light nucleus, e.g., ^{3}He with $r_E \simeq 2$ fm, the nucleon is indeed quite large. In particular the elastic proton radius is much larger than derived from the very successful dipole fit to the form factors, which gives $r_E^p \simeq 0.81$ fm in agreement with the first experimental evidence at Stanford. Already the later Mainz experiment resulted in $r_E^p \simeq 0.86$ fm, and recent optical and radio-frequency experiments measuring Lamb shifts etc. lead to radii as large as (0.90-0.92) fm. In such a situation the 3 nucleons in ^{3}He require already 30 % of the nuclear volume, and the situation becomes more and more crowded for heavier nuclei.

Real and virtual Compton scattering determine the polarizabilities of nucleons and nuclei, and thus provide an excellent testing ground for effective field theories (see review talk by B. Holstein). Already the leading order of ChPT, at $\mathcal{O}(p^3)$, predicted $\alpha = 10\beta \simeq 12 \times 10^{-4}$ fm^3 for the nucleon, with α the electric and β the magnetic polarizability. These predictions are in good agreement with recent experiments at SAL and MAMI in the case of the proton. Experiments to measure the polarizabilities of the neutron by scattering off heavy nuclei gave contradicting results, and this has revived the interest in photon scattering off "neutron targets". In this situation it is very promising that effective field theory provides an excellent fit to recent SAL data for elastic Compton scattering off the deuteron (see lecture of H. Grießhammer).

The question whether elementary particles are spherical or intrinsically deformed has intrigued many authors (see lecture of L. Tiator). Since the nucleon cannot stabilize a quadrupole moment, we have to extract such evidence from the NΔ-transition. Expressed as a ratio of electric quadrupole to magnetic dipole transition, a value of $R_{EM} \simeq -(2.5 \pm 0.1)$ % has been derived, which in a simple model transforms into a small oblate deformation of the $\Delta(1232)$. The NΔ-transitions have also been studied by electroproduction in order to determine $R_{EM}(Q^2)$ and the associated ratio for Coulomb transitions, $R_{SM}(Q^2)$. While perturbative QCD predicted that $R_{EM} \rightarrow 1$ for $Q^2 \rightarrow \infty$, the data indicate that R_{EM} remains small with a tendency to cross from negative to positive values at $Q^2 \simeq 3$ (GeV/c)^2.

According to the sum rule of Gerasimov, Drell and Hearn (GDH, see contributions of R. Gilman an R. Van de Vyver), the anomalous magnetic moment κ of a system with finite spin is related to the integral $I = \int d\nu(\sigma_A - \sigma_P)/\nu$ where ν is the photon lab energy and σ_A, σ_P are the cross sections for absorbing a circularly polarized photon on a target with antiparallel and parallel spin, respectively. The sum rule predicts $I^p = -204$ μb and $I^n = -234$ μb for proton and neutron, respectively, and for the two most common "neutron targets" the values $I(^2\mathrm{H}) = -0.6$ μb and $I(^3\mathrm{He}) \simeq 2I^n$. A simple comparison shows that the deuteron does not behave as an ensemble of two loosely bound nucleons, and that ^{3}He is far from being a perfect neutron target. Instead, the contributions of Δ excitation in ^{2}H are canceled by nuclear excitations to nearly 3 decimals, mainly by the low-lying $^3S_1 \to ^1 S_0$ transition (de-magnetization). In the case of ^{3}He, on the other hand, the nuclear effects add to the subnucleonic ones. Therefore, a quantitative description of magnetic moments and excitation spectra of nuclei is only possible if the model also provides a mechanism for nucleon resonance and/or meson production. Since the sum rule is based on fundamental symmetries and theorems (e.g., Lorentz and gauge invariance, causality, and unitarity), a good fit to ground state magnetic moments and the nuclear excitation spectrum only (say below pion threshold), will presumably be at variance with these elementary principles of physics!

The integrand of the GDH sum rule has now been measured at MAMI in the range 200 MeV$< \nu <$ 800 MeV, and with some theoretical input for the energies below and above this range it seems likely that the sum rule is indeed fulfilled. Similar theoretical approaches fail to reconstruct the sum rule for the neutron. That there may be a problem, indeed, is also indicated by the very preliminary results of various JLab experiments. If the preliminary findings should concretize, they could lead to a further "spin crisis", or more prosaically, call for a more thorough analysis of final state interactions and other nuclear effects in our favorite neutron targets. It is the purpose of these JLab experiments to measure the GDH integrals generalized to virtual photons, i.e., for helicity cross sections depending on both ν and Q^2. We may visualize these investigations as probing the nucleon from the coherent response at small Q^2, due to resonances and other excitations involving the entire system, to incoherent scattering off the constituents at larger Q^2, eventually point-like current quarks if Q^2 goes to infinity. The detailed results that can be obtained from such data bridge the gap between low-energy effective theories and high-energy perturbative QCD. As such they are likely to provide invaluable information on the realm of nonperturbative phenomena of QCD, which is the natural habitat of nucleons and nuclei, and hence of all ordinary matter of the universe.

1.2. Remarks by J. L. Friar

Scales and Pictures

One of the biggest changes in nuclear physics that has occurred in the past decade or two has been subsuming the quark substructure of hadrons as an integral part of our field. Particle physics has now begun to distance itself from QCD, as higher energies (and the particles associated with them) have sung their siren's song. What then of our traditional picture of nuclei as systems of interacting nucleons and mesons? Is it now obsolete?

How one views a physical system (that is, what "picture" one uses to describe it) depends on the size, momentum, and energy scales that characterize that system. A good example is an atom, which can be taken to be hydrogenic for simplicity. The characteristic size of the atom is given by the Bohr radius, a_0, while the (internal) momentum and energy scales as $\hbar/a_0$ and $\hbar^2/a_0^2 m_e$. Thus the electron mass, m_e, and the size scale, a_0, characterize the atom's properties, which is hardly a surprise given the uncertainty principle and the virial theorem. No property of the nucleus enters this description except its charge (implicit in a_0), even though every nucleus, from a proton to the transuranic elements, has a rich excitation spectrum and characteristic size and momentum scales of its own. Those scales are, however, mismatched with the atomic scales by many orders of magnitude, and only experiments with the most extreme accuracy can detect the effect of the nuclear size on atomic energy levels. For almost any application in an energy regime characterized by eV energy scales our "picture" of an atom can ignore nuclear degrees of freedom and properties (except for its charge, of course) because of the utterly dominant atomic length scales (compared to nuclear length scales). It would be highly uneconomical to compute the atomic energy levels while incorporating a nuclear Hamiltonian.

Switching energy scales to GeV electron scattering from atoms (unavoidable, because stripped-ion targets are unavailable), one typically ignores the atomic binding (or electronic) aspects, because the very energetic incident electron simply brushes aside the bound electrons with almost no change in momentum. Because of this mismatch of energy scales our "picture" of the atom in this case is simply that of a bare nucleus; the bound electrons are irrelevant. It would be highly uneconomical to calculate electron-nucleus scattering and simultaneously worry about atomic structure in the target atom.

Neither of these two views of an atom is complete, and neither is wrong. The message is that the scales of the problem determine the proper "picture", and the picture determines which set of physics tools are most appropriate for a theoretical description of a physical system.

Of more immediate interest is our picture of a nucleus. Is it a collection of nucleons or a collection of quarks? Both are correct, and one must appeal to scales to determine the best "picture". At low energies our simplest, most economical description is in terms of nucleons. After all, a photon with energies of a few tens of MeV causes nucleons to be ejected from a nucleus, and the ejection mechanism (via Siegert's theorem) is semiclassical for nucleons. At much higher energy scales the parton picture is best. A meson-nucleon picture becomes increasingly problematic as energy increases. For example, each added meson in a meson-exchange-current calculation at sufficiently high momentum transfers has an effect as large as any of the other components. This is a signal that our "picture" is becoming uneconomical, and economy of description eventually sides with partons or some equivalent description.

What is the energy scale at which a nucleon-based picture transforms into a parton-based picture? A rough answer is $\Lambda \sim 1$ GeV, the (generic) energy of QCD bound states (such as $\rho, \omega, \ldots,$ mesons). This is also the scale used to organize Chiral Perturbation Theory (CPT), which can be viewed as a mapping of QCD onto effective degrees of freedom (nucleons and pions). Note that although massless QCD has no intrinsic scale at the classical level, any *effective* theory based on composite particles will have associated scales. CPT can be shown to generate a series in (Q/Λ), where Q is of order 1-2 $m_\pi c^2$ inside a nucleus. For energies Q approaching Λ this picture (and the theory underlying it) breaks down, and alternative pictures become more economical and thus more attractive. All of these examples illustrate why degrees of freedom for a given system are a *choice*, not an obligation, and different degrees of freedom (corresponding to regimes with different scales) lead to different "pictures" of the same physical system.

This organizational scheme has practical consequences for nuclear physics. Large nucleon separations correspond to small momenta, which is the domain of CPT. Small distances correspond to high momenta, where CPT works less well. A nucleon-nucleon potential therefore has two interesting and very different regions: a large-r region where calculations based on CPT are possible, and a small-r region where appeals to short-range physics, or phenomenology, must be used.

The long-distance aspect of the NN force was described at the conference in two talks by the Nijmegen and Bochum groups. The Nijmegen phase-shift analysis has successfully incorporated one- and two-pion-exchange potentials in the tail of the NN force (including isospin violation), as well as the usual long-range forces of electromagnetic origin. The interior of the force is handled phenomenologically. Their results are impressive; the two-pion-exchange components lead to a reduction in the fitted χ^2, which is insensitive to the location of the boundary between the two regions, as long as that boundary is outside 1 fm. This demonstrates that we know the form of the tail of the NN force.

The short-range part of the force is necessary, of course, but for NN energies known to be important for calculating the low-lying levels of light nuclei, only a few moments of that force are needed, which explains why very different models of that short-range force are equally successful. In CPT all of the short-range physics is subsumed by moment operators of just this type (δ-functions and their derivatives), whose strengths must be determined phenomenologically. Only the division of this force into momentum-dependent and momentum-independent parts can be expected to generate significant uncertainty in few-nucleon calculations, provided that the potentials themselves are credibly fit to the NN data. If one desires an explanation of the short-range physics that doesn't devolve on phenomenology, one must again shift pictures and seek an explanation at the quark level.

Thus the division of nuclear physics into short-range and long-range parts, with different pictures associated with each part, is not a problem for the field, but rather a necessary response to the scales of the problem under consideration. Significant advances have been made recently by exploiting these pictures, and by choosing appropriate physics tools to treat them.

1.3. Remarks by V. R. Pandharipande

Wave functions at small internucleon distances

One of the persistent questions in nuclear physics has been the meaning of the nuclear wave function at small internucleon distances, r_{ij}, up to ~ 1 fm. The NN scattering data, used to obtain realistic models of the two-nucleon interaction v_{ij}, contains information only on the asymptotic, large r_{ij} behavior of the wave function. Particularly, after the identification of the quarks and gluons as the principle participants in the strong interaction, the meaning of the wave function calculated from a Hamiltonian containing only the nucleon degrees of freedom, at small r_{ij}, becomes interesting.

The main short range structure in the calculated nuclear wave functions is similar in all nuclei [1], and in nuclear matter [2]. This was conjectured in the fifties by Bethe and Levinger [3]. In the isospin $T = 0$, spin $S = 1$ state this structure has the shape of a toroid of ~ 1 fm diameter and ~ 0.8 fm thickness, while in the $T = 1,\ S = 0$ state the wave function has a peak at $r_{ij} \sim 1$ fm. The length scale of these structures is comparable to the rms charge radius of the proton of ~ 0.8 fm. However, the dipole form of the form factor suggests that the proton charge density has approximately an exponential form given by $\sim 3.3e^{-r/0.23}$ with a length scale of only 0.23 fm.

Fortunately the interesting toroidal structure in the $T = 0;\ S = 1$ state can be observed by elastic electron-deuteron scattering. The deuteron electromagnetic form factors have been studied at many laboratories in the past decades; most recently at the Jefferson Lab [4–6]. The observed form factors are rather well explained with deuteron wave functions calculated from realistic v_{ij}. The main qualitative features are obtained with just single nucleon currents, while relatively small pair currents are necessary at the quantitative level. Therefore the data strongly suggests that the deuteron wave function $\Psi(\mathbf{r})$, calculated from realistic v_{ij}, has the conventional physical meaning; $|\Psi(\mathbf{r})|^2$ gives the probability density for finding nucleons with relative separation $\mathbf{r}$, even at $r \sim 1$ fm.

If, when two nucleons are less than a fm apart, the resulting six valence quark state has little overlap with the two-nucleon state, then the wave function at small internucleon distances need not have such a simple meaning. Unfortunately, the valence quark wave functions of even single nucleons are not that well understood. The underlying three-body problem can be solved, but models of three-quark Hamiltonians are not as well developed as, for example, the three-nucleon Hamiltonian used to treat ^{3}H and ^{3}He. Until recently there were no methods to solve the six-quark problem underlying the valence quark structure of the deuteron. Now one can use the quantum Monte Carlo methods developed for ^{6}Li and ^{6}He [7] to obtain the ground states of six valence quarks from model Hamiltonians.

Recently Paris and myself [8] used a nonrelativistic flux tube quark model with one gluon and pion exchange interactions to study the two-nucleon problem using quantum Monte Carlo methods. We essentially put the six quarks in a cavity with diameter $R_C = 2, 4$ and 6 fm, and found their ground state wave function with variational Monte Carlo methods. We studied quark pair distribution functions as well as quark color correlation functions.

When $R_C = 6$ fm, the quark pair distribution function at $r \sim 1$ fm is similar to that in isolated nucleons showing clustering of quarks into a two-nucleon state. But when the cavity diameter is $R_C = 2$ fm, the quark pair distribution function deviates significantly beyond $r = 0.4$ fm from that in isolated nucleons. However, the color correlation functions are essentially the same for these values of R_C and very close to those in free nucleons. It thus appears that, at least in this model, the quarks cluster into two nucleons at all R_C. When R_C is small the quark structures of the two nucleons penetrate each other significantly, but without much distortion. The ground state of this model can therefore be well approximated with a two-nucleon wave function whose short range part has the simple physical meaning. The deviation of the quark pair distribution function at $r > 0.4$ fm, for $R_C = 2$ fm, is due to contributions from quarks belonging to different clusters, but each cluster is very close in structure to a free nucleon. Under such conditions the ground state of a nucleus can be well approximated by an A-nucleon wave function even at length scales smaller than the nucleon size. The quality of the approximation depends primarily on how well nucleons penetrate each other without too much distortion.

1.4. Remarks by I. Sick

Nucleonic degrees of freedom

The invited talks and contributions presented at this meeting have demonstrated impressive progress in the area of the understanding of the nucleonic few-body systems. Starting from different nucleon-nucleon (N-N) potentials fit to N-N scattering data, the Schrödinger equation can today be solved with virtually no approximations. For bound systems, this is the case for mass numbers up to A=10, for continuum states up to A=3, and higher for selected observables. The extension of exact methods to *continuum* states is particularly important as many of the observables employed to study the few-body systems do involve continuum states.

It has been shown that for these few-body observables different calculational techniques give the same results. With the exception of a few cases, the calculations find excellent agreement with the data, to the point where the calculated results often look like "fits" to the data. It is particularly satisfactory to see that these predictions now have been extended to nuclei as heavy as A=10. For the first time, these exact calculations are no longer limited to the "singular" cases A=2, 3, 4; exact predictions now do concern nuclei that are part of "mainstream" nuclear physics. This progress is impressive. The good agreement between calculation and data shows that we have, for bound states and continuum states at not too high energy, the right degrees of freedom: (basically) nonrelativistic nucleons bound by the N-N interaction known from N-N scattering.

There are some loose ends, though. The three-body (3BF) force, needed to get ground state binding energies and splittings in neutron-rich nuclei right, is still a phenomenological one, and its properties are not well enough constrained by the data. We still lack a sufficient number of *specific* observables (such as the binding energies and the minimum in p-d scattering at $\sim$200 MeV) to fix the 3BF. Here further progress is needed.

Mesonic degrees of freedom

The mesonic degrees of freedom play an important role, particularly in electromagnetic observables. In this area, much progress has been made during the last years, and is documented in a number of the talks presented at the conference. The meson exchange currents (MEC) today can be calculated such as to be largely consistent with the N-N interaction employed. These MEC often give large effects. The present calculations are quite effective in reproducing the experimental data. A new window to MEC has been opened with the *precise* experimental data on NN$\rightarrow$ NNγ and $\rightarrow$ NNe^+e^- that recently have become available. While such data in the past were thought to provide information on the off-shell N-N interaction, it now has become clear that their main usefulness lies in the study of MEC. With the addition of *polarization* observables, this reaction will further enhance our understanding of MEC.

This picture of nucleons bound by the N-N interaction and MEC consistently derived from the N-N interaction — the "standard model of nuclear physics" — works amazingly well. It actually does better than could be expected, and it is successful at higher momentum transfers, where it could (should) be expected to break down. The deuteron electromagnetic form factors, F_{C0}, F_{M1} and F_{C2} recently extended to larger Q, is perhaps the most striking example.

Again, there are some loose ends: The interplay of MEC and relativistic effects needs to be better controlled, and MEC terms not derivable from the N-N interaction, such as terms involving dynamical Delta's or the $\rho\pi\gamma$ exchange currents, are still too uncertain.

Quark degrees of freedom

In this area of the understanding of nuclei in terms of quarks, gluons (q, g) and QCD, relatively little progress has been reported. This area of activity is clearly one of the future.

While it is clear that nucleon and meson degrees of freedom are the dominant ones —

and the most efficient ones — needed to understand nuclei, we do want to understand nuclei in terms of the degrees of freedom for which we believe to have an *exact* theory, QCD. There is hardly a need to understand all nuclei in terms of these degrees of freedom; one would like, however, to understand some *simple* nuclei, such as the N-N-system, in terms of these more fundamental constituents. One important question is: where to look to find observables that do depend specifically on the q, g? Systems with very few nucleons are certainly preferred, as there we understand the nucleonic structure best. Electromagnetic observables at large momentum transfer carry the greatest promise for sensitivity to short internucleon distances, the place where the role of q, g should be the most visible. This search for q, g degrees of freedom presumably will have to start from the *understood* nucleonic and mesonic structure. It does not seem practical to start from the perturbative regime as the data that can be measured for nuclei never reach momentum transfers Q high enough — Q *per constituent* much larger than internal momenta of the constituents — to make pQCD estimates valid. (Of course, one can always carefully select observables that might look like pQCD estimates.) The difficulty then resides in the problem to find observables that are sensitive to the q, g structure in a situation where much of the known observables are explained in terms of nucleons and mesons. We clearly need better theoretical predictions for 2,3-body nuclei in terms of q, g such that we know where to look, and we need data at higher momentum transfers to get to the regime where the q, g degrees of freedom might dominate.

1.5. Remarks by F. Gross

Significant progress

I have been very impressed and pleased with the progress our field has made during the last decade. This progress is a backdrop to this conference, and even though it has not been very explicitly discussed here (except, perhaps today during the session on nuclear systems with A $\geq$ 3) I want to include it in this mini-summary. Specifically, I want to single out the following developments:

- **Beautiful, high precision calculations of 2, 3, and 4 body systems.** This work is exemplified by the wonderful calculations of the Bochum group reported at other conferences by Glöckle and Epelbaum, and by the new developments on accurate 4-body calculations being done by Viviani, Fonseca and others. However, I am told that there is "trouble in River City[1]", and that discrepancies in 4-body calculations may soon occupy our attention. I look forward to hearing about this in a future conference.

- **Fundamental explanation of the binding energies of A $\leq$ 10 nuclei.** To be able to calculate the structure of all nuclei directly from fundamental 2, 3 (and perhaps 4) body forces has been a dream and goal of nuclear physics since its inception. We heard about the recent progress of the Argonne-Illinois group this morning. It is now possible to believe that it will eventually be possible to understand all nuclei directly in terms of fundamental forces.

[1] A reference to the American musical *The Music Man*

- **New, high precision data.** The beautiful new medium energy electron scattering data from Jefferson Laboratory, Mainz, and Bates, and the low energy nucleon scattering data from TUNL are continuing to challenge this field. We have entered a period where the data and theory both enjoy the precision for which few body physics is famous. Without both we cannot explore such issues as the A_y puzzle, the GDH sum rule for the neutron, or scaling (violations?) in high energy deuteron photodisintegration.

Effective field theory

Perhaps the most significant new developments reported to this conference are the applications of effective field theories to the few nucleon problem. These were reported in the very nice talk by Grießhammer, and in the reviews of the recent results in the theory of nuclear forces reported by Timmermans and by Epelbaum. I must confess that I have believed for some time that effective field theory was nothing more than a jazzed-up version of Bethe's effective range theory, but have begun to change my mind. Each of us must make our own reassessment of old issues in this new light. For my part I have begun to believe (again) in the importance of finding "controlled expansions" and in estimating "theoretical errors", ideas which many of us believed in when we were young and eventually dropped because we were unable to see any way to realize them. These tools are integral to effective field theory, and should encourage us all to return to the ideals of our youth. The precise methods being used today may not be the ones to survive, but hopefully any new methods will use controlled expansions and permit the estimate of theoretical errors.

For myself I was particularly impressed by the result that inclusion of the *long range* part of the two pion exchange mechanism considerably improves the phase shift analysis (as reported by Timmermans). This result would have been no surprise in the early 50's when one was still filled with hope that pion exchange would hold all the answers to understanding the nuclear force. Two things went wrong in those days: (i) chiral symmetry was unknown and γ_5 coupling for the pion was used (giving pair contributions that were too large) and (ii) clean methods for treating the divergences and unknown short range forces had not been developed. One of the most satisfying principles of effective theory is that the short range force may be very important, *but the physics must be insensitive to the details of this force, and it may be fully taken into account by introducing only a few adjustable parameters.* This answers the puzzling question of how to get the short range NN force "right". Finally, I was particularly impressed with Grießhammer's demonstration that a non-zero three-body force is needed to stabilize the *nd* effective range calculations. Food for thought!

Theoretical issues

I will conclude by commenting on a number of theoretical issues discussed at this conference.

- **Off-shell effects:** It is commonly stated that "off-shell effects" are unobservable. This is of course true, but so are wave functions, potentials, and most of the theoretical tools we use to describe physics. A better point is that off-shell effects are *meaningless without a theory or model to define them.* Almost all models provide such a definition, and off-shell effects should be discussed only in the context of a particular model that defines these effects *uniquely*. Then the results of calculations will be sensitive to such effects because *off-shell effects always mock-up, in some approximate way, "higher order" contributions.*

- **Three body forces and currents:** These are also not measurable, and like off-shell effects are defined and created by the theory.
- **Relativistic effects:** Recent progress was well reviewed in the excellent talks by Wallace and Şavkli. This is no longer a new subject, and the lack of consensus on how to calculate is not a license to ignore the more than 30 year literature. Some of the many contributed papers on this subject did not explain clearly what was new or better about their work, and did not place their contribution in the context of this 30 year effort.

None of these effects are directly observable, and because of the freedom provided by unitary transformations, are *not uniquely defined except in the context of a particular theory* (which should specify the "phase" of the unitary transformation). They are also often dependent on the reference frame in which they are calculated. Such ambiguities provide a rich opportunity for meaningless arguments.

Finally, I want to call attention to the nice talk on bosonization by Vento. We all believe in duality, but understanding will only come when we find models that give the same results using *either* quark-gluon *or* meson-nucleon degrees of freedom.

2. CONFERENCE DISCUSSION

2.1. The questions

The panel drafted three questions to guide the conference discussion that is reported below. These questions were published in the Conference Handbook, and displayed at plenary sessions in advance of the discussion. The questions are:

1. Based on our best current knowledge of nuclear theory and experiment, at what distance or energy scales (if any) is the nucleon best described as a bound state of quarks, and at what distances or energy scales (if any) as a bare nucleon surrounded by a meson cloud? What evidence is there to support, or refute, the notion that a nucleon retains its essential character inside of a cold nuclear medium?

2. What are the main uncertainties in the present models of nuclear forces and currents, and what new experiments/theories are needed to remove them?

3. What are the most successful predictions (or post-dictions) of modern nuclear theory? Why do we have confidence in these predictions?

In the discussion that followed, the panel chair required that the first few comments on each question come from members of the audience, with panel members contributing only after the discussion was underway. After a slow start, the discussion picked up and was thoughtful and lively, and was not dominated by the panel.

2.2. The discussion

2.2.1. Question 1: Degrees of freedom

Rosina began the discussion by noting that many calculations treat even broad resonances as quasi-bound states of quarks, and wondered how much these widths would influence the present fits to excitation spectra. Will they improve or get worse? He also commented on the long standing problem of dibaryons. Models that give similar results for hadronic spectra may give very different predictions for dibaryons, as discussed widely in the 1980's. He asked why nothing conclusive had been seen experimentally. Was something wrong with quark models? **Rupp** replied that unitarized quark models often gave large real mass shifts, sometimes even predicted that some states were absent. **Pandharipande** said that progress on this problem at the quark level required solutions of the six-body problem. **Gross** pointed out that decay rates had been calculated with the gluon exchange models, and that it only remained for the meson exchange model people to do the same. In fact, these predictions of decay rates showed that some resonances couple strongly to $N\gamma$ and $N\rho$ or $\Delta\pi$ (ending up as $N\pi\pi$ final states), but only weakly to $N\pi$ states. Such resonances would be "missing" in πN scattering, but could be detected in the photoproduction of $\pi\pi$ final states. The search for such "missing resonances" was (and is) one of the justifications for the Hall B program at Jefferson Lab.

Oberhummer asked how he should "draw" a neutron for a popular audience. He thought he would find out at this conference, but now he is more confused than ever. Should he do it at the quark level, or at the pion level? In response, **Gross** said that he has a colloquium style slide of the neutron with two different views: one with a thick pion "skin" and a small quark core, and one with a very thin pion skin and a big quark core. He said that he likes to tell colloquium audiences that nuclear physicists are not sure which picture is more appropriate. But stimulated by this discussion, he asked the audience whether this way of phrasing the question was even appropriate. Maybe both views are correct? **Drechsel** reminded the audience that measurements of the neutron charge form factor already gives an answer to this question. There are two parts to the neutron, a small bag reaching out to about 0.7 fm and a cloud of negatively charged pions outside. So if we speak about quark models we must also speak at the same time about quark-antiquark fluctuations, or pions. Even the Δ resonance cannot be described in a quark model without pions. About 30% or more of the excitation strength can be attributed to pions. **Drechsel** thinks meson exchange currents are a result of the pion cloud surrounding a nucleon. **Machner** said that deep inelastic scattering shows that there is a distribution of quarks but no "bag". **Grießhammer** brought effective field theory into the discussion. At intermediate range there is really no good model independent way to think of a nucleon between the extremes of the quark picture and the simple point-like nucleon plus pion picture. **Kleefeld** said that it was important not to mix bases; we can work consistently with a quark-gluon basis or a meson-nucleon basis.

Wallace asked if it was really important to solve QCD to get the inner part of the NN interaction. **Sick** said that it is important to be able to explain at least one simple nuclear system, such as the deuteron, in terms of the underlying quark and gluon degrees of freedom. In the same way that we are content to use an effective theory to understand lead after we have demonstrated that light nuclei (A<10) can be explained directly from the Schrödinger equation, we should be content to use nucleons and mesons to understand carbon after we have shown that the deuteron can be explained directly in terms of quarks and gluons.

Friar brought the discussion back to scales. For example, in atomic physics it is not necessary to understand the structure of the nuclear core of the atom; all that is needed is the charge, mass, and radius. In practical terms, we really must use the scales appropriate to the problem at hand. **Pandharipande** thought that scales were not really the correct issue. For example, in deep inelastic scattering (DIS) from ^{4}He, it is clear that quarks are the correct degrees of freedom. The correct question, he thought, is whether or not DIS from ^{4}He can be understood from the knowledge of DIS from a single nucleon *plus* the ^{4}He wave function for the bound state. **Sick** said that the length scale of a nucleon (to be described in terms of quarks and gluons) is not very different from the length scale of a nucleus. Because these are not so different, one should be able to describe both in the same framework. If they were very different, as in the atomic case, one might use totally different degrees of freedom. **Adam** said that the discussion had separated so far into scales where quark degrees of freedom are needed, and scales where effective field theories are useful. What about intermediate distances where nucleon or meson resonances are important? **Gross** concluded the discussion of this question by saying that we might all agree that at very high energies quarks were clearly the best degrees of freedom to use, and at very long distance scales mesons and nucleons were most efficient. What we really need is a model at intermediate range that shows how the *same* result can be obtained by using either quark-gluon or meson-baryon degrees of freedom. Such an example will show how descriptions based on these two very different degrees of freedom compare and in what circumstances one is better than the other. **Sick** reminded us that, in the context of the study of large nuclei, this happened several years ago when it was shown that the same physics could be described by either the shell model or by cluster models. In this case a formalism for transforming from one description to another existed, and this helped show when one was more effective that the other.

2.2.2. Question 2: Uncertainties

Rupp began this part of the discussion with a short story. As a student he had "searched the complex energy plane for a unitarized S-matrix", and had discovered the σ! Unfortunately, no one paid attention. Recently, new data has led to a rebirth of interest in the σ and other scalar mesons. If it turns out that there is a real light sigma around 500 MeV, how would it affect the effective field theorists, the chiral quark model builders, and the believers in the linear sigma model? A participant suggested that re-analysis of old data may give a light sigma. **Friar** said that, from the viewpoint of effective field theories, a light sigma could be a problem. This already happens in the baryon sector, where some believe that the Δ, a low lying state, must be built into effective chiral perturbation theory from the start. If these low lying states are frozen out, the convergence of the effective theory may be too slow. It is a matter of efficiency. **Kleefeld** pointed out that the pion and sigma of the linear sigma model are different from the pion of the nonlinear chiral Lagrangian (and any sigma that might be added to the nonlinear theory). **Gross** said that he thought that whether or not the sigma was "real" did not matter to our description of the NN force. Even if there is no low mass resonance, we know that there is a lot of $\pi\pi$ strength at a range of 500 MeV, and this strength can be represented by a phenomenological sigma exchange in the NN force. **Timmermans** reminded us that his recent results show that the uncorrelated two pion exchange contribution obtained in the context of chiral perturbation theory is sufficient to describe the intermediate range attraction; no explicit sigma is needed.

Vento emphasized that the new effective theories have changed our view of renormalization. Non-renormalizable effective theories introduce parameters that must be fit to data. He emphasized that we know that QCD is the theory of the strong interactions, and that therefore the main task must be to calculate these effective parameters from QCD. The only thing QCD has to explain is the parameters of effective field theory. With respect to few body theory, he agrees with Wallace; if we have the correct effective theory, "who cares about QCD". QCD will enter only through the determination of the parameters of the effective theory. Models are a way of imitating QCD, and must be simple. If they are not, we might as well solve QCD. The advantage of models is that they are speculative, and that we may use them to predict a range of phenomena or study the impact of changing the parameters of the theory. The next speaker returned to the sigma, and said that one of the cleanest ways to study the sigma is through final state interactions in K_{l4} decays, or even D_{l4} where a large kinematic range is available.

Fonseca then wanted to "leave the sigma in peace" and change the subject. He called attention to the fact that three body forces and other effects that are small in the three body systems and seem to be under control are, in fact, much larger and less well understood in the four body sector. The nt system is the simplest scattering system that exists in the four nucleon sector, and has a lot of rich structure that does not seem to be possible to explain using our present force models. If we cannot explain it, our whole atmosphere of content with our present understanding of NN forces "goes down the drain". He would like us to prove that our current models are either "right" or "wrong." This issue should be settled soon. The Pisa group should produce a convergent calculation at 3.5 MeV. Even if this agrees with the nt scattering data, there may be problems with dd scattering, where the present results are also terrible. He suggested that the next conference focus on four body physics; the calculations and the experiments are now ready for it.

Kleefeld asked if there really is a "standard model" of nuclear physics? With respect to the sigma and the rho, for example, there is a lot of ambiguity. How do we define the parameters that are to be calculated from QCD? He thought that there really was no standard model of NN interactions. **Sick** said that the "standard model" assumed that you started from a parameterized NN interaction and did not ask how the parameterization came about. Then you used this model to compute nuclei, and in this sense the standard model is successful. If, however, we want to calculate nuclei in terms of quarks and gluons, then we do not have a standard model. **Friar** added that there are potential models without sigmas and rhos, but only pions plus phenomenology. He reminded us that for low energy phenomena effective field theory tells us that it really does not matter what we put at short range, as long as we have a few parameters for each channel.

2.2.3. Question 3: Predictions

Gross, steering the discussion to the third question and building on Fonseca's previous remarks, said that it is very important that we can be proven either right or wrong. If we can always change the model to adapt to any new physics, we have no ability to predict or explain. Where have we been able to make definite predictions (or post-dictions) in the past? What do we really know? **Grießhammer** asked what is the goal. He said there was a wide range of approaches: some are interested in the conceptual sides of things and others may be engaged in a kind of "nuclear engineering" in the sense that they want to explain the binding energy of the deuteron to 0.1 keV. He asked the panel where the balance should be? **Adam** posed another question. Taking moderate momentum transfer measurements of T_{20} from elastic electron deuteron scattering as an example, he thought that neither quark models nor effective field theories had anything to say. What do we learn from such measurements? Should we forget about them? **Pandharipande** responded to this last question by pointing out that, in his view, one of the triumphs of simple potential models of nuclear physics is that they were able to predict T_{20} to "sub-femtometer" precision. He also cited the ability of potential models to predict $d(e, e'p)n$ scattering up to 800 MeV missing momentum, and deuteron form factors. It is completely false to ignore measurements that cannot be predicted by quark models or effective field theories.

Sick returned to the question of nuclear engineering. To be taken seriously, he believes we need be able to achieve accuracies of 1% in kinetic energies or potential energies. If we are satisfied with accuracies of $\sim$30%, this field will not be taken seriously. Some "nuclear engineering" is needed; accuracy at the 10^{-2} level is satisfactory and gives us understanding (with some loose ends). In general there is no need to go to the 10^{-4} level. **Vento** said that chiral effective theories must be able to explain the deuteron, the "Ferrari" of nuclear physics, if they want to be successful. **Kirchbach** wanted to place this discussion of nuclear engineering in a philosophical context. In the sense of Thomas Kuhn, nuclear engineering reflects the fact that we have a successful paradigm that allows us to solve problems with precise answers. Anomalies are problems that can either be solved within the paradigm, or may be signs of serious failures of the paradigm, but we do not know which is the case. **Kalantar** pointed out that many experimentalists are trying very hard to get high precision data, and that the precision required of the models and the data may depend on the momentum scales of the measurement. Low precision (30%) at high Q may be as significant as high precision (1%) at low Q. **Pandharipande** agreed. He described two views of nuclear physics. One is the intellectual view where we seek the connection between quarks and gluons. On the other hand there is a huge amount of nuclear engineering which has to be done in order to understand the evolution of the universe. Nuclear physicists must understand the origin of nuclei. The low energy data is more relevant to this latter issue. **Friar** agreed, saying that nuclear physicists may not "own" quarks, but they do "own" nuclei, and if we cannot understand nuclei we are in real trouble. **Kleefeld** asked how we can have precision at the 1% level without understanding isospin breaking in pions? **Sick** said that if isospin breaking is important, it must be included, and **Pandharipande** said that most modern NN potentials did include the mass differences of the pions.

The discussion shifted to quark confinement. It is a central problem at the foundation of nuclear physics, and particularly so for few nucleon physics. **Sick** believes that our current use of the light front to analyze deep inelastic scattering is less than satisfactory; we need to connect the analysis of DIS to the ground state wave functions of the target in the rest frame. **Gross** reminded the audience that numerical solutions of QCD on the lattice show linear confinement. Someone asked what issues nuclear physicists were most worried about. In response, **Pandharipande** said he was worried about not having a Hamiltonian to describe nuclear matter and light nuclei at the same time.

Gross brought the discussion to a close by noting that there had not been much discussion of successful predictions. He regretted that there was not more time for this discussion.

It was announced that the next International Few-Body Conference will be hosted by the Triangle Universities Nuclear Laboratory (TUNL) and held at Duke University in North Carolina, USA, in 2003. The organizers of this European conference were applauded and thanked, and the conference was closed.

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